Fluctuations of Broadband Acoustic Signals in Shallow Water

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Award Number: N00014-10-1-0396
http://oalab.cms/udel.edu

LONG-TERM GOALS

The long-term goal of this project is to obtain quantitative understanding of the physical mechanisms governing broadband (50 Hz to 50 kHz) acoustic propagation, reflection, refraction, and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

OBJECTIVES

The scientific objective of this research is to understand acoustic wave propagation in a dynamic environment in two frequency bands: Low (50 Hz to 500 Hz) and Mid-to-High (500 Hz to 25 kHz). The goal for the low frequency band is to assess the effect of internal waves on acoustic wave propagation, with an emphasis on the mechanisms that cause significant acoustic temporal and spatial intensity fluctuations. The goal for the mid-to-high frequency band is to assess the effects of water column and dynamic sea surface variability, as well as source/receiver motion on acoustic wave propagation for underwater acoustic communications, tomography, and other applications.

APPROACH

This project is a continuation of previous project entitled “Fluctuations of Mid-to-High Frequency Acoustic Waves in Shallow Water” award number: N00014-07-1-0546**.** Combined experimental, theoretical, and modeling efforts are devoted to improve our understanding of broadband acoustic wave propagation in a dynamic shallow water environment. Studies in the low frequency band have utilized data from the SW06 experiment collected in summer 2006 with both stationary and moving sources [1]. A 3-D numerical modeling has been developed to investigate different mechanisms that can explain acoustic intensity fluctuations in the presence of internal waves. The detailed 3-D environment data required as input to the model has been constructed using temperature and radar image data.

Studies in the mid-to-high frequency band have utilized data collected at the HFA97 [2] and KAM08 experiments [3]. The effects of sea surface and water column variability, as well as those of a moving

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Fluctuations of Broadband Acoustic Signals in Shallow Water**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,College of Earth, Ocean, and Environment,Newark,DE,19716**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

source, on acoustic wave propagation have been investigated using both a Parabolic Equation and ray-based models. The models are also utilized to explain specific features observed in the received signals.

WORK COMPLETED

1) *Low Frequency Acoustic Wave Propagation.* Progress has been made in understanding the horizontal focusing/defocusing that occurred when the internal wave front and acoustic track aligned closely. Based on shipboard radar images and temperature data collected at various locations along the acoustic track, a detailed 3-D environment was reconstructed for a 3-D parabolic approximation model to study the unique propagation scenario [4]. Data and model comparisons are in good agreement.

2) *High Frequency Acoustic Wave Propagation.* A computationally efficient model to study the effects of sea surface roughness on the high frequency acoustic propagation has been developed by combining an acoustic ray-based model Bellhop with a time-evolving 2-D surface wave model [5]. Model result of arrival time-angle fluctuations due to sea surface roughness compares well with data from HFA97 experiment and suggests that there are physical processes which need to be included in the model such as bubbles and turbulence as well as out-of-plane scattering effects.

   Both stationary and moving source data in KAM08 have been analyzed to assess the effects of source movement and environment variability on the acoustic wave propagation for acoustic communications. Results from preliminary runs of parabolic equation model with evolving 2-D sea surface representation are in good agreement with data. More runs are required to fully explain the features observed in the received signals.

3) *Instrumentation.*
   An acoustic multiple-input/multiple-output (MIMO) transmission/acquisition system has been developed on the University of Delaware Gavia AUV [6]. The MIMO transceiver system is capable of simultaneous transmissions of up to four data streams as well as acoustic reception via eight hydrophones from a towed array. The system has been calibrated and tested successfully during two deployments in Delaware Bay.

RESULTS

A. Low Frequency Acoustic Wave Propagation in the Presence of Shallow Water Internal Waves

The mechanism of internal wave effects on the acoustic wave depends on the angle between the internal wave and the acoustic wave [7]. Three main mechanisms that are possible include refraction, mode coupling, and adiabatic mode.

During the SW06 experiment conducted in New Jersey shelf, an acoustic source was towed by the R/V Sharp and followed the front of an internal wave packet. The source was transmitting broadband acoustic signals (50-450 Hz) in different angles with respect to the internal wave front. The received signals were analyzed to study the horizontal focusing/defocusing that occurred when internal wave

front and acoustic track aligned closely. Focusing of sound in the horizontal plane is a special case of refraction problem.
In order to model the acoustic propagation in the presence of internal waves, the 3-D environment was reconstructed based on the shipboard radar images of R/V Sharp and R/V Oceanus and temperature data collected on three thermistor strings. The data were linearly interpolated in three directions: parallel and perpendicular to the internal wave front, and *z* direction. The radar images were used to check the shape of the interpolated field and the speed of its movement. Recent study has shown the ducting effects by curved internal wave [8], but in this study the internal wave front are assumed as straight lines for computational simplicity while still generating good modeling results. Figure 1 shows the reconstructed 3-D environment with radar images from R/V Sharp and R/V Oceanus [4].

Figure 2 shows model-data comparison of one of the 3-D Cartesian Parabolic Equation model results during the transmission time M2 when the internal wave started to cut into the acoustic track. The model [Fig. 2(b)] successfully predicts the happening and the timing of the focusing event.

Figure 3 shows the horizontal ray hitting the receiver. Panel (a) shows the temperature at 15 m, which is approximately the depth of the source speaker. Panel (b) is the depth integrated sound intensity, compensated for the cylindrical propagation loss. The temperature plots on panel (c) and (d) show the position of the source was at the tough of the internal wave when the focusing happened.

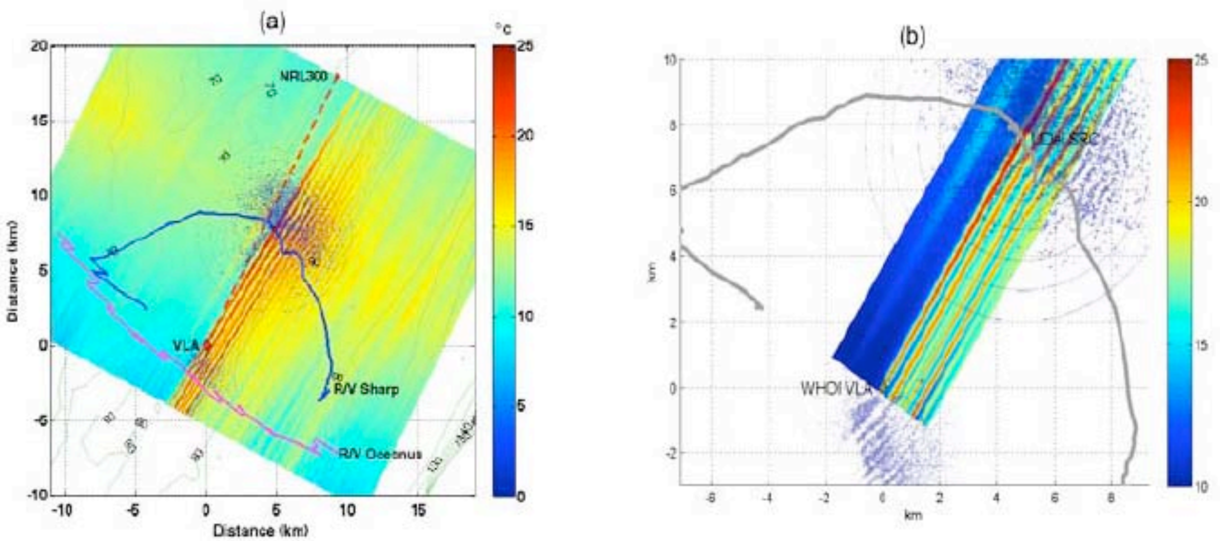

Figure 1: (a) Reconstructed 3-D environment based on temperature data from three thermistor strings with radar image overlay for 21:45 GMT on August 17, 2006; (b) Zoomed-in view showing the detailed surface of internal wave images from radars on 2 ships [4].

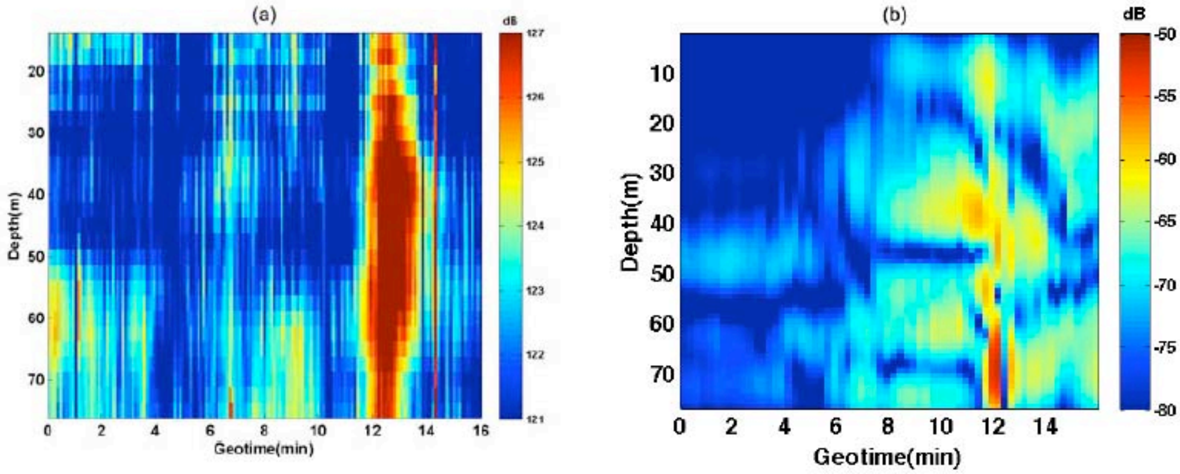

Figure 2: (a) Measured signal on WHOI VLA; (b) 3-D PE modeling result using the reconstructed environment condition during M2 transmission when the internal wave started to arrive at the acoustic track. The model successfully predicts the happening and the timing of the focusing event [4].

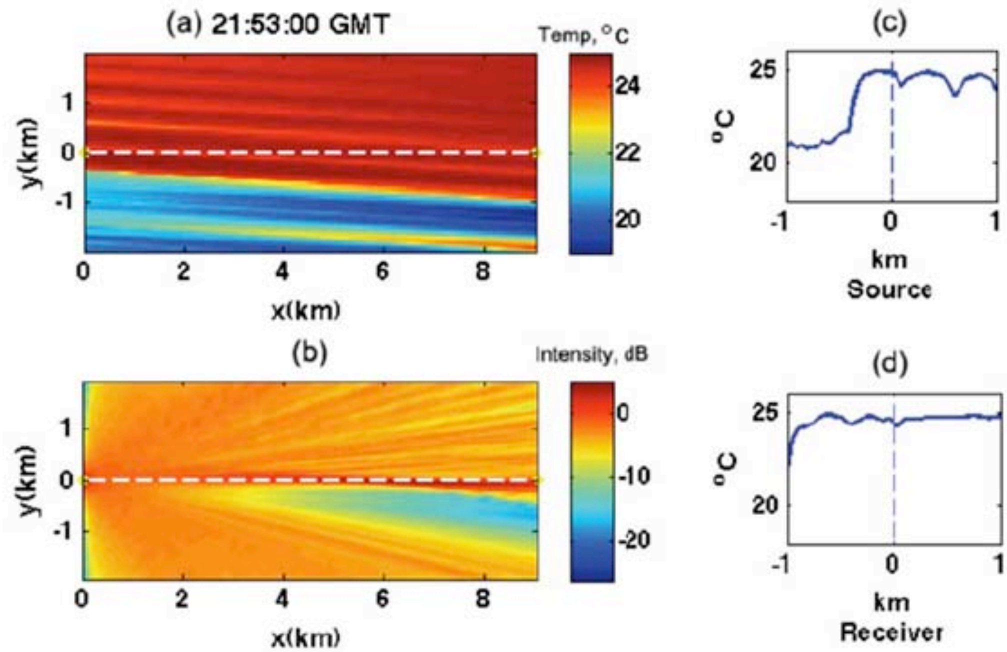

Figure 3: (a) Top view of temperature field (depth = 15 m) at 21:53 GMT on August 17, 2006; (b) A horizontal plane slice of the 3-D PE results showing the depth integrated acoustic intensity; (c) temperature at the source; (d) temperature at the receiver [4].

B. High Frequency Acoustic Propagation in Shallow Water

Surface waves are among several environmental parameters that can have significant influence on underwater acoustic propagation in shallow water. We have developed two models to study the effects of surface wave roughness, i.e. ray-based and Parabolic Equation models using a 2-D time-evolving sea surface as boundaries.

I. Ray-based Model

Acoustic ray methods are attractive for high frequency modeling problems because they are very much less computationally intensive while providing satisfying results compared to fullwave acoustic models. An existing acoustic ray-based model Bellhop [9] has been combined with a realistic 2-D time evolving sea surface model [10, 11] to simulate efficiently the effects of sea surface roughness on acoustic wave propagation in coastal regions [5]. Rough sea surface realizations are generated and used as sea surface boundaries in the acoustic model. The results are then compared against a unique set of experimental data collected during the HFA97 experiment in Delaware Bay. These data include simultaneous environment and acoustic propagation (1-18 kHz) measurements.

Figure 4 illustrates the approach used in this study to achieve higher resolution in the model while maintaining computational speed. Since we only consider the single surface only reflected rays then instead of using a large range of ray take-off angles to cover a large portion of the surface, we need only to consider a smaller range of $\Delta\theta$, which insonifies ΔR part of the surface within several surface wave lengths from the specular point. Hence with the same number of rays, as with larger range of take-off angle, model resolution is increased while maintaining the same computational time.

Model-data comparison of standard deviation of arrival time and angle as a function of wind speed are shown in Figure 5. Data show that arrival time and arrival angle fluctuations increase as wind speed increases, which is also predicted by the model. Notice that there is a large spread in the data, especially during high wind speeds. The model underestimates the fluctuation of arrival time especially during high wind speeds, suggesting that there are physical processes which need to be included in the model, such as bubbles and turbulence effects as well as 3-D or out-of-plane scattering.

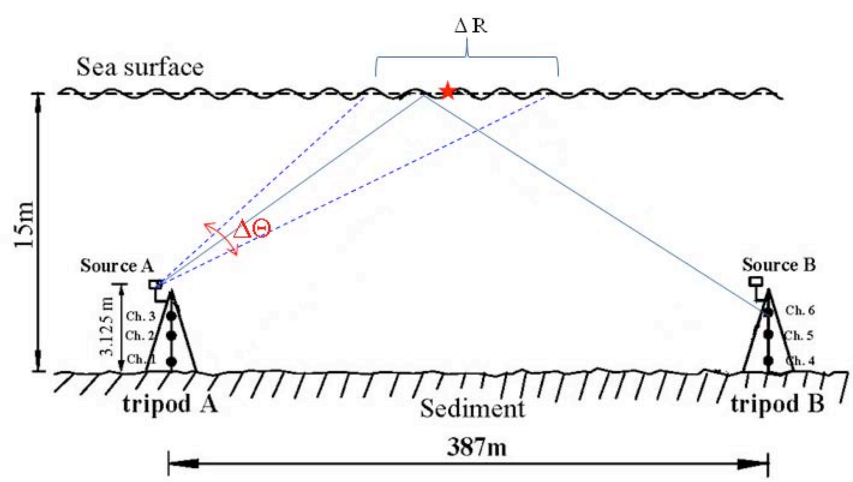

Figure 4: Sketch of small ray fan used in the model to achieve higher resolution while maintaining computational efficiency of the ray-based model. Red star indicates the specular point [5].

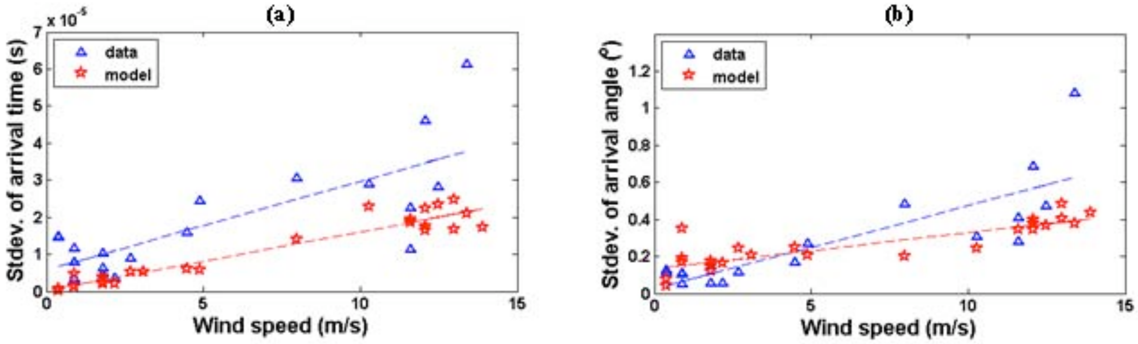

Figure 5: Model-data comparison of standard deviation of (a) arrival time and (b) arrival angle as a function of wind speed. Red triangles and blue stars are data and model, respectively. Lines are linear fit of the values. Notice that there is a large spread in the data, especially during high wind speeds [5].

II. KAM08 Experiment and Parabolic Equation Model Results

Data in KAM08 have been analyzed to assess the effects of sea surface roughness on acoustic wave propagation for acoustic communications. Micro multi-paths were observed from surface-interacting paths, and their variability has been examined for a variety of surface conditions. A surface wave model has been integrated into a parabolic equation model (MMPE) [12] to approximate variations in the micro multi-path structure over geo-time. Model results were used to examine the correlation between environmental variability and observed single-bounce signal fluctuations. Comparisons have been made with a variety of surface wave conditions, ranging from calm to rough seas. As an example, Figure 6(a) shows the ensemble averages of transmission loss vs. arrival time data for 30 s transmissions with a 0.25 s repetition-time under calm and rough surfaces, while figure 6(b) shows PE model results for separate flat and rough surface realizations. These plots emphasize the acoustic energy spread of rough surfaces relative to calm surfaces, an artifact that was observed during the KAM08 experiment and replicated using the rough surface PE model [13]. This PE model has been extended so that it is capable of providing realizations for time-evolving rough surfaces. Figure 7(a) shows 12 successive PE runs with time-steps of 0.125 s, while figure 7(b) shows the first 200 m of the rough surface used to generate these successive runs.

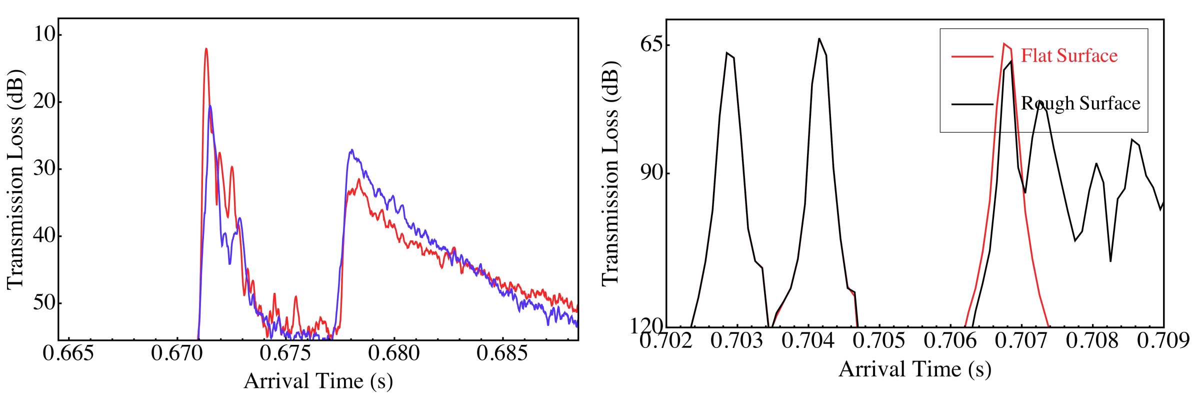

Figure 6: (a) Ensemble average of transmission loss for 30 s transmissions with 0.25 s repetition time during calm and rough periods. (b) MMPE results for flat and rough surface cases.

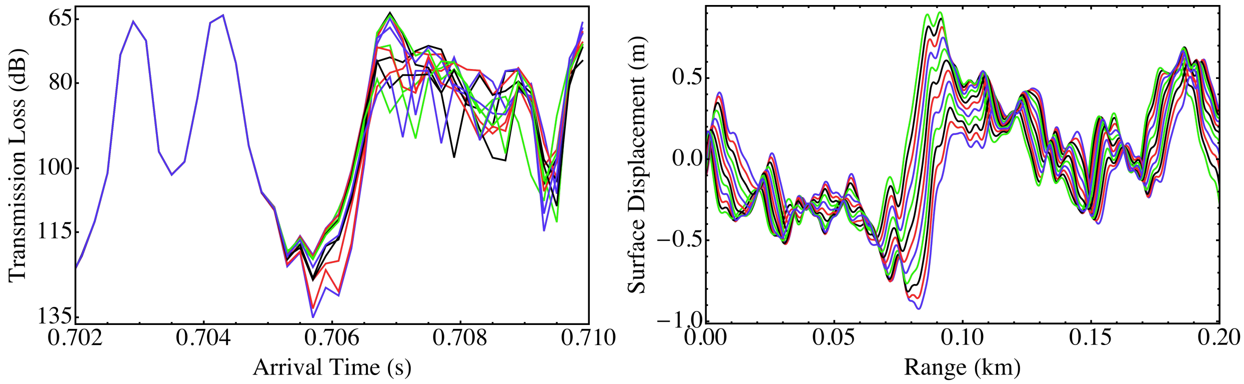

Figure 7: (a) Transmission Loss for rough-surface transmissions with time steps of 0.125 s. (b) Rough surfaces used to generate respective runs shown in 7(a).

C. Instrumentation

The MIMO module designed for the UD Gavia AUV has successfully completed two deployments in Delaware Bay. The module is consisting of 3 transmitting units and one 8-channel receiving unit. Each transmitting unit has its own amplifier and transducer, and can transmit with up to 130 watt of power. The high frequency receiving unit can continuously record at sampling rate of 80 kHz/sec/ch.

The first deployment involved an analysis of the MIMO's ability to execute commands (issued to the AUV while on the surface), maintain steady connectivity with the AUV and transmit sets of chirps and experimental M-Sequences. The AUV traversed a 1 km path away from the *R/V Donna M.* before executing a 180 degree turn and transiting back to the vessel. An 8-channel acoustic array was deployed off the stern of the *Donna M.* to record the MIMO transmissions.

On August 26th 2010, the MIMO module was again deployed in Delaware Bay. The mission was to test higher intensity M-Sequences to ensure clear reception and distinction from the background noise of the ocean. The AUV followed a zig-zagging path, and the signal at three different ranges were recorded by the 8-channel array deployed from the *Donna M.* Analysis of the data is currently taking place.

IMPACT/APPLICATIONS

The low frequency component of our research contributes to the understanding of acoustic propagation in complex shallow water regions. We have developed a model to explain the focusing/defocusing of acoustic intensity caused by internal solitons. The high frequency part of our research has contributed to the understanding of the effects of surface wave roughness on sound propagation, which in turn affect the performance of acoustic communication signals.

RELATED PROJECTS

In the low frequency band research, we have been working with Dr. J. Lynch at Woods Hole Oceanographic Institute (WHOI) and Dr. B. Katsnelson from University of Voronezh, Russia. For the research work in the high frequency band, we are collaborating with colleagues from Scripps Institution of Oceanography (Dr. W. Hodgkiss and Dr. H.-C. Song), Applied Physics Laboratory-

University of Washington (Dr. D. Rouseff), Naval Post Graduate School (Dr. K. Smith), and Heat, Light, and Sound Research Inc. (Dr. M. Porter).

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PUBLICATIONS

[1] J. Luo, M. Badiey, and Y.-T. Lin, "Horizontal focusing/defocusing due to shallow-water internal waves," *JASA, POMA*, Vol. 9, 2010.

[2] E. A. Karjadi, M. Badiey, and J. T. Kirby, "The impact of surface gravity waves on high frequency acoustic propagation in shallow water," 159th Meeting of the Acoustical Society of America, Baltimore, Maryland, 19-23 April, 2010.

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